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Geotechnical and infrastructural damage due to the 2016 Kumamoto earthquake sequence

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ABSTRACT:

An active sequence of earthquakes (foreshock, main-shock, and aftershocks) hit the Kumamoto area (Japan) in April 2016, resulting in 69 deaths and considerable economic loss. The earthquakes induced numerous ground failures and cascading geo-hazards, causing major damage to important infrastructures. The main damage patterns include: (a) surface rupture with widespread subsidence of the surface ground, resulting in damage and disruption to transport infrastructure; (b) landslide and slope failure of mountains causing severe damage, collapse and near-collapse of bridges; and (c) liquefaction in some areas of Kumamoto City. Following the earthquakes, field surveys were conducted to study the damages and to understand the main cause of the observed failures. This technical note provides a summary of the geotechnical and infrastructural damage in Kumamoto and the lessons learnt and future research needs are also highlighted.

Keywords: 2016 Kumamoto earthquakes, Liquefaction, Bridge, Damage, Subsidence, Fault rupture

1.0 INTRODUCTION

Overview of the earthquake damage

A sequence of two strike-slip earthquakes occurred on 14th and 16th April 2016 in Kyushu Island, southern part of Japan. Japan Meteorological Agency (JMA) reported a magnitude of $M_j 6.5$ (moment magnitude $M_w 6.1$) for the 14th April foreshock and $M_j 7.3$ (moment magnitude $M_w 7.1$) for the 16th April main-shock, respectively. The total number of fatalities due to the earthquakes is reported to be 69, while the total number of casualties was 1,747. The estimated total economic loss is 24 to 46 billion US dollars. The earthquakes destroyed 8,050 houses and 24,147 buildings suffered major damage. Historically, there have been damaging earthquakes in the Kumamoto region. For instance, the $M 6.3$ 1889 earthquake caused notable damage in Kumamoto City (20 deaths, 54 injuries, and 239 house collapses). However, the damage severity and earthquake impact of the 2016 earthquakes are far greater than these relatively recent damaging earthquakes in Kumamoto.

The earthquakes triggered numerous landslides in the mountainous areas of Kumamoto and destroyed major infrastructure and facilities. In the plain areas of Kumamoto, several sections of Kyushu Expressway (bridges and road surface cracks) were damaged due to the ground shaking, induced subsidence, fault movement and liquefaction. This resulted in major disruption of the regional traffic network. The operation of the railways was also severely affected due to derailment of trains (both Shinkansen and local train) and damage to the railway tracks owing to large landslides. Following

the earthquakes, a series of damage surveys were carried out to record and understand the various aspects of the damage. The aims of the paper are to:

- (a) Summarize the seismological aspects of the earthquakes together with the details of the fault rupture and characteristics of the input motion in the near-fault region.
- (b) Present the observed damage of buildings, bridges and infrastructures with a focus on the geo-hazards.

2.0 SEISMOLOGICAL ASPECTS OF THE EARTHQUAKE

The double events that occurred on 14th and 16th April were of right-lateral strike-slip type occurring at shallow depths with the respective focal depths of 11 km and 12 km and originating from different active faults which are very close. A very active sequence of earthquakes was also observed in the Kumamoto region, after the triggering foreshock event of 14th April 2016 as depicted in Figure 1. The first event originated from the northern segment of the Hinagu fault, while the latter was caused due to the Futagawa fault which runs NE of the Hinagu fault, see Figure 1 which also shows the spatial distribution of earthquakes occurring over a period between 1 April 2016 and 31 May 2016. The foreshock induced an active sequence of dependent events, clustering along the Hinagu fault. Subsequently, the mainshock occurred on the southern tip of the Futagawa fault, and triggered an even more active subsequence of aftershocks. The aftershock sequence is not only concentrated along the Futagawa-Hinagu faults but also in the Aso region. The migration of seismic activities over a relatively wide spatial scale is a notable feature of the 2016 Kumamoto earthquake sequence. Further details of the seismological aspects can be found in Goda et al (2016) and Fujiwara et al (2016).

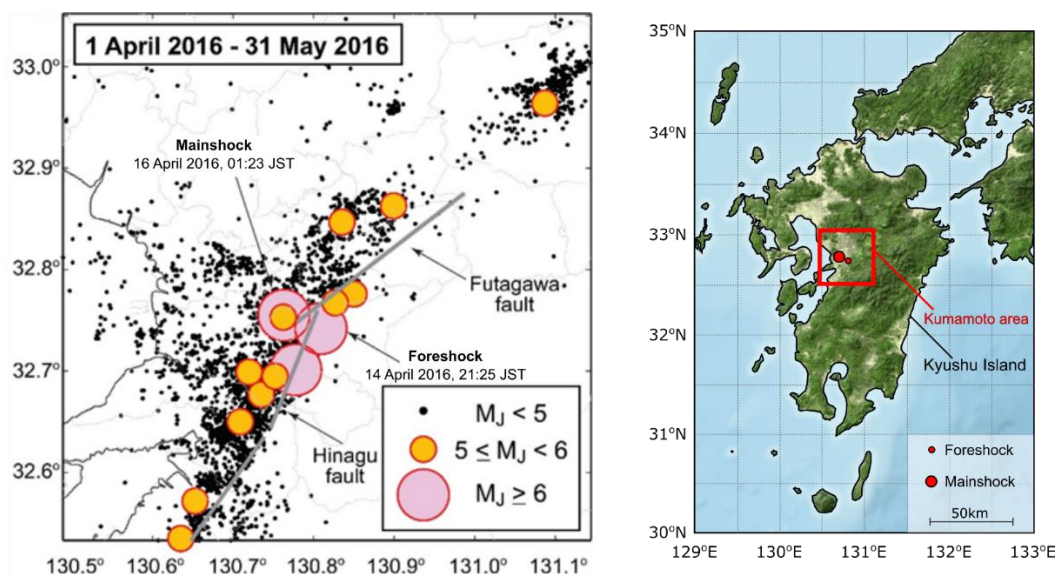


Figure 1: Spatial distribution of earthquakes (foreshock, main shock and aftershocks)

The JMA intensity of 7 (highest intensity in the JMA intensity scale) was recorded in Mashiki Town during both the foreshock and the mainshock (i.e. double shocks) and thus many buildings had collapsed. Figure 2a shows observed velocity time-histories (3 components) at KMMH16 for the mainshock. KMMH16 is a KiK-net station in Mashiki Town; two sets of 3-component ground motion data are available, one at ground surface and the other at the borehole. The blue curves are for the ground surface recordings, whereas the red curves are for the borehole recordings. The significant

amplification of the ground motions can be visually inspected by comparing the blue and red curves. Another notable observation is that for the velocity time-histories for the main-shock, relatively large long-period velocity waves are present at both ground surface and borehole (particularly for vertical motions). This indicates that site amplification for short-period components is significantly influenced by near-surface soil characteristics, while that for long-period components is more coherent at ground surface and borehole. The latter may also be attributed to the ground surface rupture near the Mashiki areas. To examine the spectral content of the observed ground motions at KMMH16, 5%-damped response spectra for the main-shock are calculated and shown in Figure 2b. The results for the ground surface motions are presented with solid lines, while those for the borehole motions are shown with broken lines. The comparison of the response spectra indicates: (i) amplitudes of the response spectra are large, exceeding $1,000 \text{ cm/s}^2$ (circa 1 g) up to a period of about 2 s for the main-shock; (ii) generally site amplification is significant for all three components; (iii) horizontal motions are amplified in a period range between 0 s (i.e. PGA) and about 2 to 3 s , while vertical motions are significantly amplified at vibration periods less than 0.5 s .

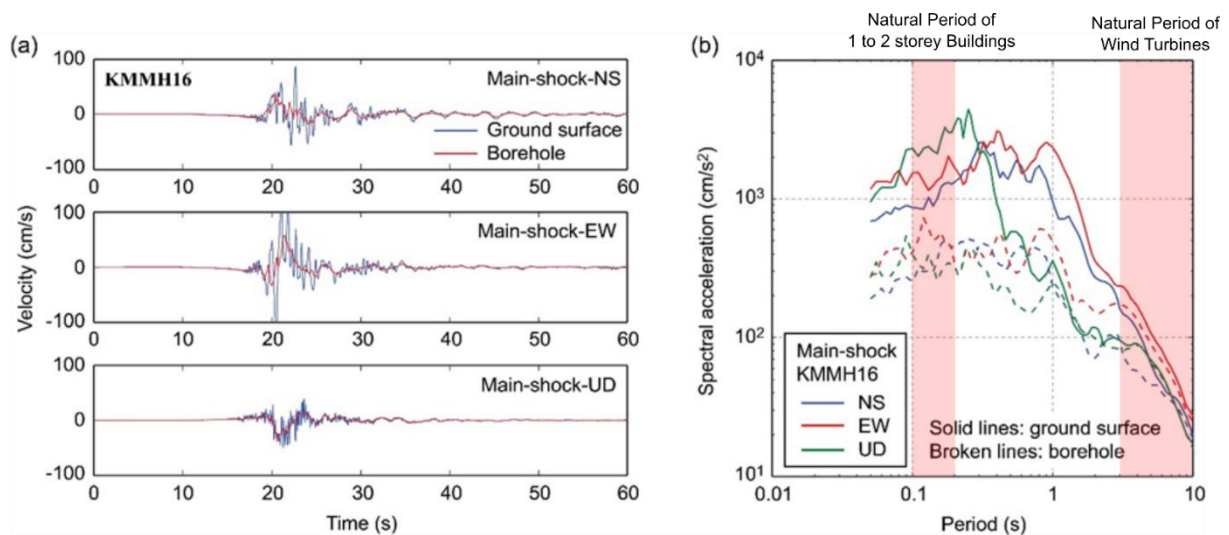


Figure 2: (a) Earthquake velocity time histories; (b) Acceleration spectra

3.0 GEO-HAZARDS

The 16th April main-shock caused significant damage in wider areas near the fault, such as Mashiki Town, Nishihara Village, and Minami Aso Village. The widespread damage caused by the main-shock was caused by multiple cascading geological hazards. The geo-hazards observed in the area are discussed below:

- **Fault movement**

In the near-fault region, the effects of the ground deformation were remarkable: buildings and infrastructure that were directly above the fault rupture were damaged severely. The crustal deformation due to the mainshock was observed as ground surface rupture at many locations along the Futagawa fault. At several places, ground deformation up to 2 m was observed. Figure 3 shows surface fault movement of 1.5 m observed in Aso City (Uchinomaki area) and the private house narrowly escaped severe damage. The secondary damage was caused by landslides and other ground failures, including liquefaction, settlement, and lateral spreading along rivers and coastal areas. The earthquake damage was widespread over the rural areas of Kumamoto Prefecture.



Figure 3 (a): Subsidence due to fault movement close to buildings [Before and after the earthquake]

- **Landslides**

Typical landslides were observed at different locations including Aso Bridge and Minami Aso, see Figure 4. Severe landslides and surface fault rupture have been observed around the Minami Aso area. The hazards include mud and debris flow, applying kinematic loading on infrastructure, such as bridges. It has been reported that 10 people were killed by large-scale landslides in the Minami Aso area. Furthermore, large-scale landslides near Choyo Bridge were also observed. The landslides were located at the downstream of Aso Bridge where significant damage to the slope and bridge occurred. Other landslides were located west of the Minami Aso area, near Nishihara Village.



Figure 4: Landslide near Aso bridge area.

- **Liquefaction**

Surveys of the affected area following the earthquake showed signs of sand boiling with ejected sand on the surface. Liquefaction were observed in Kumamoto Port, Akitsu River (Mashiki Town), Kamiezu Lake and a stretch (a rectangular belt) covering 2km by 20m between Shirakawa River and Midorikawa River in Kumamoto City as shown in Figure 5. The possible explanation is that the area was an old natural river dike which was reclaimed. Figure 5 also shows selected borehole profiles along the survey route. The ground consists of Alluvium relatively new deposit overlying Diluvium. The top soil is black colored organic possibly of volcanic nature, locally known as Kuroboku. Simplified JRA code based liquefaction analysis was conducted on the ground profile and it is predicted that 0m to 8m may have liquefied. Typical liquefaction damages in the area can be seen in Figure 6, which shows several buildings show differential settlement in Kumamoto City. It was interesting to note that high rise buildings and most possibly supported on pile foundations performed well except some minor damage

in line with the expectation as observed in other earthquakes, see Bhattacharya et al (2011).

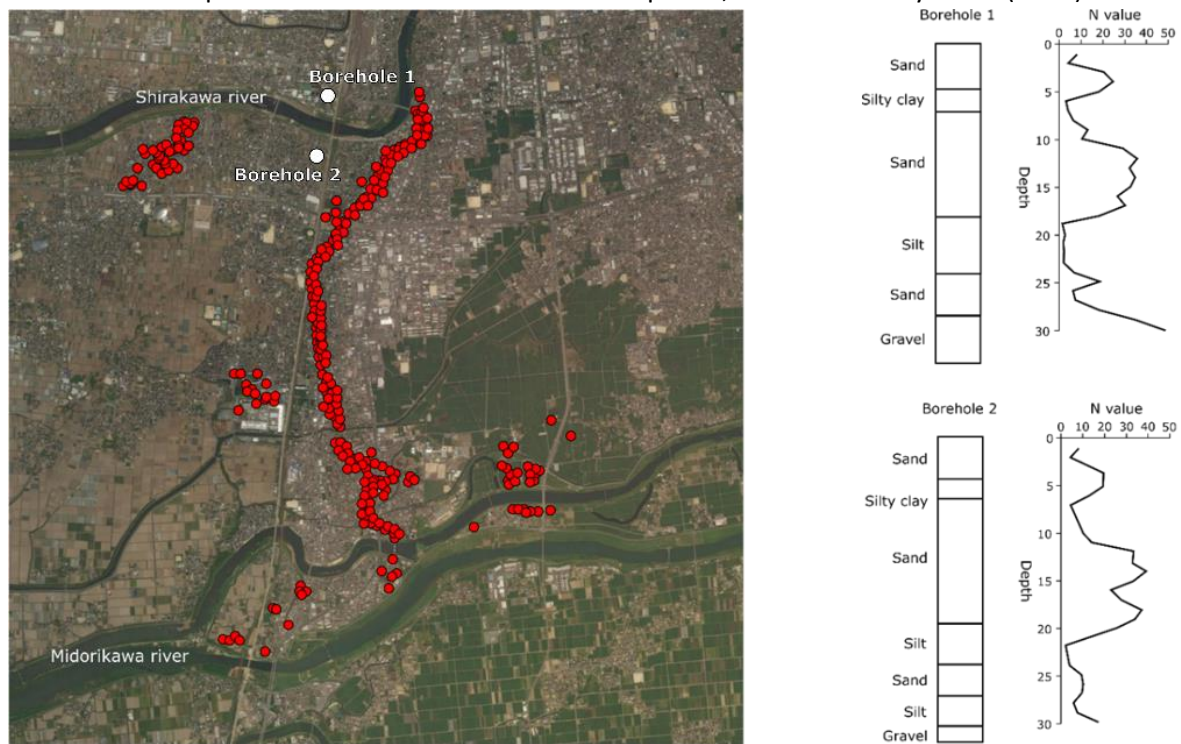


Figure 5: Observed liquefaction along the survey route; (b) Sample borehole data



Figure 6: Liquefaction induced damage to buildings in Kumamoto

4.0 DAMAGE TO CRITICAL INFRASTRUCTURE DUE TO GEO-HAZARDS

The combination of all the geohazards discussed, caused severe damage to the Kumamoto infrastructure. Because of liquefaction many cases of lateral spreading, differential settlements of the ground were observed along the river resulting in pavement cracks, sinkholes, and uplifted manholes. Moreover, within the residential area, the polyester bags filled with soil and wrapped with polythene were laid along the embankment as a temporary protection measure. However, the landslides occurred in the area had the most destructive coincidence. The landslides occurred in the area adjacent to steep incised rivers and streams, where the natural soil or fill materials overlying the bedrock flowed away. Severe cracking of ground, which is associated with landslides, were usually observed resulting to the damage of multiple key infrastructures, such as Aso Bridge, Oogiribata Bridge, Choyo Bridge, and Tawarayama Tunnel, disconnected main access routes (e.g. Route 57 and

Road 28) between areas inside and outside Aso Caldera. More details on these damages are given below and can be seen in Figure 7.

- **Aso Bridge**

Typical landslides damage noted are at Aso Bridge (near the student hostel of Tokai University). The slope angle was roughly 20 degrees and large flow of debris, including both rock and soil at huge quantity, was observed. Because of this large landslide in the Minami Aso area, Aso Bridge was collapsed completely, see Figure4, and the connection between Tateno and Kurokawa districts in Minami Aso Village was lost.

- **Daiichi Hatanaka Bridge**

In the southern part of Mashiki Town specifically along Kiyama river, a clear damage was noted on Hatanaka Bridge. Severe settlement at the transition area of bridge and soil ground is apparent. The bridge piers show significant damage especially underneath the pile-cap as well.

- **Tainimiyazo Bridge**

The bridge is located south of Mashiki Town. The ground settlement is approximately 40-45 cm on both the entrance and the outlet. Despite this large settlement, there was no obvious damage to the bridge piers. The large settlement of the ground may be related to the loss of soil volume due to liquefaction.

- **Tawarayama Tunnel**

Tawarayama Tunnel was located on Road No.28 with 4.5 m high, 7.5 m wide and 2057 m long. It was built in 2002. Several concrete segments lining fell down, which is a huge threat to the tunnel stability beside the development of shear cracking along the tunnel. Settlement along the tunnel was observed, and severe cracking at footing was evident as shown in Figure 10.



Figure 7: Damages to infrastructure; damage to Daiichi Hatanaka Bridge(top left); Damage to a bridge at Akitsu river (top right); Damage to Tawarayama Tunnel (bottom)

Good performance of wind turbines (energy infrastructure)

There were many wind turbines operating in the mountains and these structures performed well, as expected. The reason for good behavior can be explained based on the acceleration spectra shown in Figure 2(b). The periods of typical wind turbines are in the range of 3 to 10 seconds and the predominant period of the earthquake was in the range 0.2 to 1 second. This is consistent with the observations from the 2011 Tohoku earthquake as presented in Bhattacharya and Goda (2016).

5.0 CONCLUSIONS:

The Kumamoto earthquakes originated from two closely spaced active strike-slip faults (Hinagu and Futagawa). This is an intraplate region event having a relatively shallow focus, similarly to the 1995 Kobe earthquake. Based on the study of the fault rupture and timing of the earthquake sequences, it was very clear that the seismicity migrated both spatially and temporally (space and time). This earthquake is very different from so-called megathrust subduction earthquakes (such as the 2011 Great East Japan earthquake). The following lessons were learnt from this earthquake:

- (1) Deformation demands in the near-fault region are significant and therefore new design considerations are needed to design long linear structures such as bridges
- (2) Bridges and Tawarayama Tunnel suffered great damage during the Kumamoto earthquake. Severe settlement occurred at the transition area between bridge and soil ground. Tunnel damage, including falling of concrete segment lining and severe shear cracking on concrete segments were observed.
- (3) Liquefaction was observed along the rectangular belt between two rivers which was an old natural river dyke. This shows the importance of carrying out proper and adequate ground improvement while reclaiming land. A study of the boiled sand showed that black volcanic soil liquefied.

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